SEISMIC CALIBRATION OF GROUP ONE INTERNATIONAL MONITORING SYSTEM STATIONS IN EASTERN ASIA FOR IMPROVED EVENT LOCATION

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ABSTRACT

A consortium of institutions that includes SAIC, the Massachusetts Institute of Technology (MIT) Earth Resources Laboratory (ERL), Weston Geophysical Corporation, the Russian Institute for Dynamics of the Geospheres (IDG), and the Chinese Seismological Bureau of Sichuan Province is engaged in a research program directed toward the seismic travel-time calibration of the 30 Group 1 International Monitoring System (IMS) stations of eastern Asia. We have assembled a preliminary 3-D velocity model of the entire region, which is composed of a global background model on a 5°-by-5° grid derived from surface wave analyses, supplemented by more detailed models in regions where they are available. At present, such detailed models have been identified for a large portion of the Former Soviet Union (FSU) for which Deep Seismic Sounding (DSS) data have been used to define a 3-D velocity model of the crust and upper mantle on a roughly 40-km by 40-km grid, and for an approximately 25°-by-30° area centered on the Pakistan/Afghanistan region for which a 3-D velocity model has been defined on a 1° by 1° grid. Regional phase travel times through these 3-D models are being computed using the Podvin and Lecomte finite difference algorithm to obtain preliminary SSSC estimates for the IMS stations in this region. These initial estimates are being tested using various calibration data sets that have been assembled for this study. These include a unique set of regional arrival-time data at FSU permanent network stations from some 60 Soviet Peaceful Nuclear Explosion (PNE) tests, as well as numerous Semipalatinsk and Novaya Zemlya explosions with precisely known locations and origin times. Such data recorded near the Russian IMS stations BRVK, NRI, TIK, YAK, PDY, and AAK have now been carefully analyzed and utilized to produce travel-time residual maps with respect to both the default IASPEI91 travel-time curves and the travel time predicted by our DSS 3-D velocity model. It has been found that, for most of these stations in the stable platform regions of Russia, the travel times predicted by the IASPEI91 model are consistently too slow at distances greater than about 10 degrees by as much as 5 to 10 seconds. However, the corresponding travel-time residuals with respect to our DSS 3-D velocity model were found to be significantly smaller, with most stations showing an average bias near zero. A preliminary event location test has been conducted using data recorded near these IMS stations from 14 Soviet PNE events that were recorded at four or more stations. The results indicate that the DSS 3-D velocity model provides significantly more accurate seismic locations for these ground truth explosions than does the default IASPEI model (i.e. an average mislocation of 11.7 km as compared with 20.4 km).

In an attempt to improve our initial 3-D velocity model of eastern Asia, we are currently applying travel-time tomography to observed regional P wave arrival times from ground truth (GT) events and large earthquakes recorded at IMS and other stations. The velocity model is being parameterized in terms of crust/upper mantle velocity profiles that incorporate sediment/basement and Moho interfaces. The inversion algorithm formulation allows a subset of the model parameters, initially Pn velocity as a function of latitude and longitude, to be updated with other model parameters held fixed. The algorithm determines velocity model parameters jointly with the origin parameters of non-GT events, using grid search and conjugate gradient techniques to obtain the parameter updates. The inversion algorithm is based on the Podvin-Lecomte forward modeling of travel times, and accounts for the nonlinear dependence of travel times on both velocity structure and hypocentral parameters.

KEY WORDS: seismic, calibration, IMS, eastern Asia, SSSC, tomography

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OBJECTIVES

The purpose of this effort is to develop improved 3-D velocity models, Site-Specific Station Corrections (SSSCs), and Slowness-Azimuth Station Corrections (SASCs) for eastern Asia, to demonstrate the effectiveness of these models and corrections in improving locations of seismic events, to evaluate the uncertainties associated with these improved models and corrections, and to install these models and corrections at the Center for Monitoring Research (CMR) and evaluate their performance. The specific objectives are four-fold. The first is to collect appropriate calibration data and seismic events occurring in and around the calibration region. The second is to use these data to refine the regional velocity models and to define and refine SSSCs and SASCs for the 30 IMS stations within the region. The third is to use the new velocity models and SSSCs and SASCs with calibration data ["Ground Truth" (GT) data] to evaluate the location capabilities of the system. The fourth is to implement the SSSCs and SASCs into the location system at CMR and to work with the CMR staff to evaluate their performance in that simulated operational environment.

RESEARCH ACCOMPLISHMENTS

During the past year, we have been continuing with our effort to calibrate the 30 Group 1 IMS stations in Eastern Asia for improved seismic event location. The map locations of these stations are shown in Figure 1, where it is indicated that they are composed of 11 primary and 19 secondary stations. It can be seen from this figure that regional distance coverage circles extending to 2000-km radius surrounding these stations would encompass most of the Asian continent, so the area to be calibrated is very large and samples a wide variety of crust and upper mantle environments.

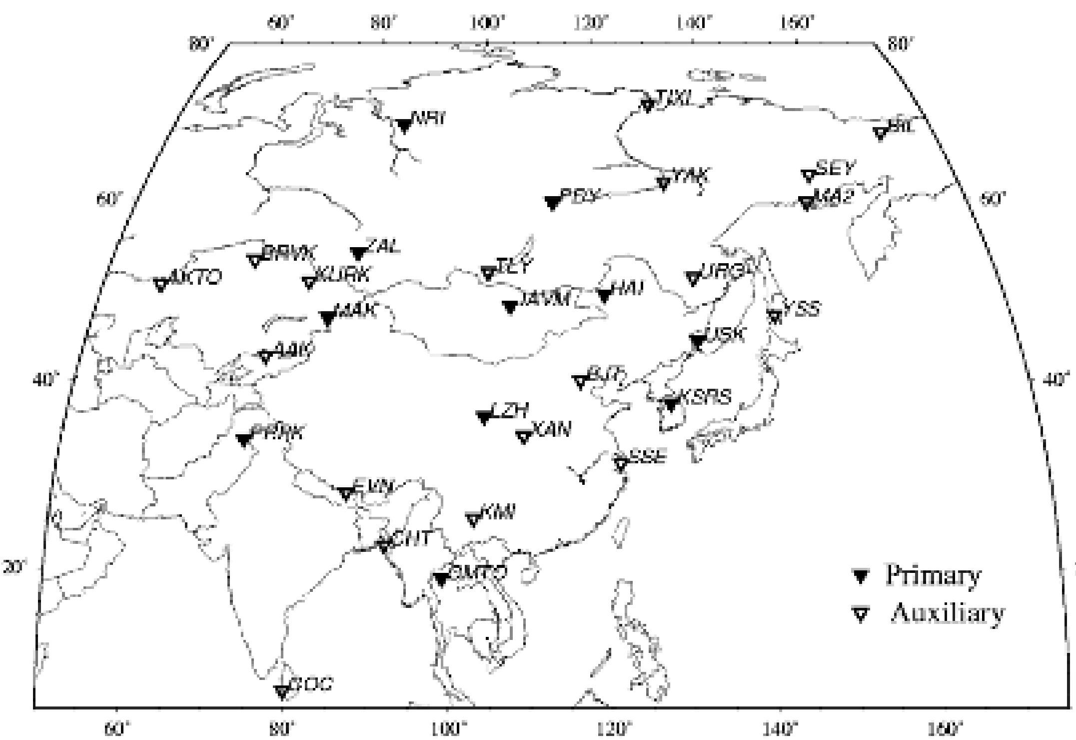


Figure 1. Map showing locations of the Group 1 IMS stations in Eastern Asia.

Our overall approach to this problem centers on the formulation of a 3-D velocity model of the region that can be used to define corrections to the default IASPEI91 model. Thus, an initial velocity model is defined from currently available information and is then refined by performing joint tomography and multiple event locations using arrival time data collected for this region. Once an optimum average model has been developed, source-specific empirical travel-time corrections for each station will be determined by interpolating between observed

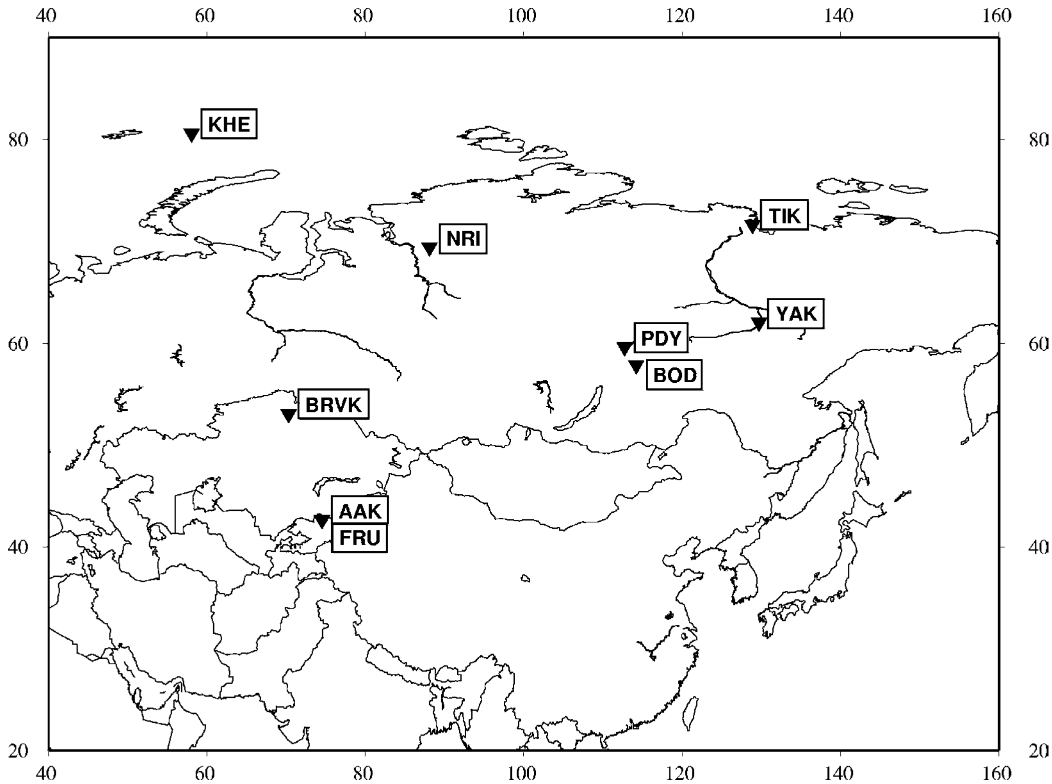


Figure 2. Map locations of seven former Soviet permanent seismic network stations (and associated IMS stations) used in the preliminary evaluation of the DSS velocity model.

calibration event residuals relative to this 3-D model. Model-based travel times determined by ray tracing through the 3-D velocity model will then be combined with these empirical corrections to generate 3-D travel-time tables for each Group 1 IMS station, and these predicted travel times will be differenced against the corresponding IASPEI91 travel times to define the required source-region-specific station corrections (SSSCs) as a function of source location around each station. This process will then be iterated to incorporate data from additional calibration events as they become available, and the final models will be validated based on relocation experiments conducted using travel-time data recorded from ground truth calibration events in the region.

Our preliminary 3-D velocity model for the Group 1 region is composed of a hierarchy of models having different spatial resolutions. A background model defined on a 5° by 5° grid covering the entire study region is derived from the global surface wave inversion results of Stevens and Adams. This background model is superceded by more detailed models in subregions where such information is available. At the present time there are two such subareas: a large region of the FSU for which Deep Seismic Sounding (DSS) data have been interpreted to obtain a detailed model of the crust and mantle on a 1/3° by 1/2° grid, and a large area centered on the Pakistan/Afghanistan region for which Weston Geophysical has been assembling a detailed velocity model (WINPAK3D) on a 1° by 1° grid (Johnson and Vincent, 2001). A software module denoted as QUILT has been developed to transform this composite spherical earth model to flat earth approximations, and to resample them to generate uniform Cartesian block models on 5- x 5- x 5-km grids extending to a range of 2000 km and a depth of 600 km for each selected IMS station. A generalized finite difference ray tracer based on one originally formulated by Podvin and Lecomte (1991) is then used to compute first arrival P wave travel times from each station to every point in the surrounding grid. Corresponding travel times for the same grids are also computed using the 1-D IASPEI model, and these values are subtracted from the 3-D travel times to obtain, by reciprocity, the preliminary SSSC estimates. These estimated corrections to the predicted IASPEI91 travel times turn out to

be quite large for a number of the Group 1 stations, and show complex spatial patterns reflecting the 3-D complexity of our initial velocity models. For example, the computed corrections for the station at Borovoye, Kazakhstan, (BRVK) range from about -10.5 to +2.9 seconds, while those estimated for the proposed IMS station near Nilore, Pakistan (PRPK) range from about -5.2 to +5.2 seconds. Clearly, corrections of this magnitude have the potential to significantly affect seismic location accuracy for regional events recorded by these stations.

Evaluation studies of the DSS velocity model of the FSU conducted to date have focused on analyses of Soviet PNE arrival time data recorded at the seven Soviet permanent network stations whose map locations are identified in Figure 2. Four of these stations (BRVK, NRI, TIK, YAK) are essentially co-located with corresponding IMS stations, while two others (FRU and BOD) are in reasonably close proximity (i.e. approximately 25 and 200 km, respectively) from corresponding IMS stations (AAK and PDY). The seventh station, KHE, located on Franz Joseph Land to the north of the island of Novaya Zemlya, is not the planned site of a future IMS station. However, data recorded at this station from Soviet PNE tests, as well as from underground nuclear tests at the two Novaya Zemlya weapons test sites, provide valuable constraints on the velocity model characteristics in north central Russia and, therefore, they have been included in this preliminary model validation study.

The ground truth regional calibration database that has been assembled for station BRVK is arguably the best available of any seismic station in the world. Support for this assertion is provided by Figure 3, which shows the map locations of some 55 Soviet PNE events within 20° of the Borovoye station for which measured arrival times are available. It can be seen that these explosion locations are remarkably well distributed around the station and, taken together with the travel-time data measured at this station from several hundred Semipalatinsk explosions, provide a unique resource for testing and evaluation studies. For this reason, we have selected BRVK as our benchmark station for the testing and evaluation of all of our proposed calibration procedures.

In the top panel of Figure 3, the symbols plotted at the PNE event locations correspond to the observed P wave travel-time residuals (observed - predicted) computed with respect to the corresponding travel times predicted by the default IASPEI91 travel time curve. It can be seen that almost all of these residuals are negative (i.e.

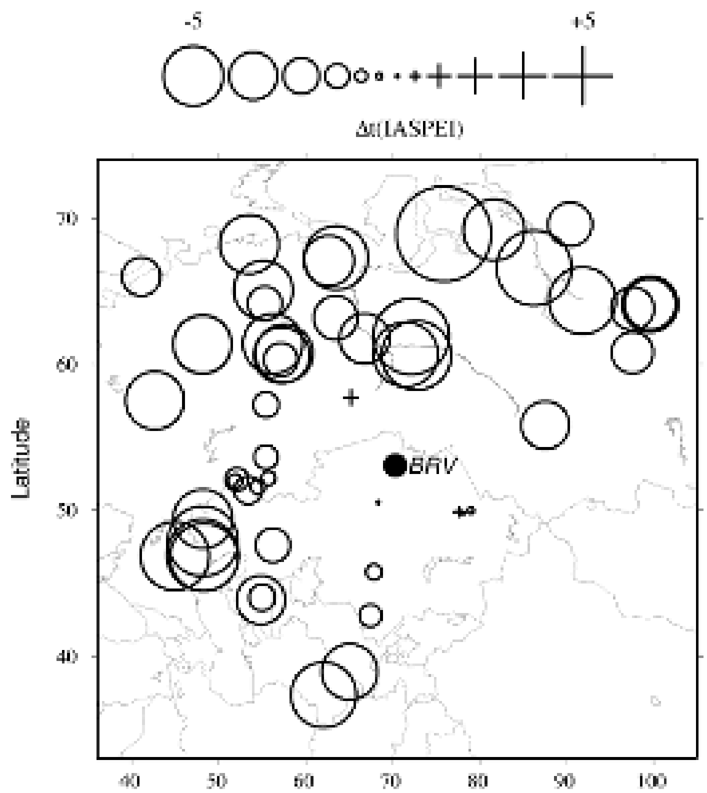


Figure 3. Map locations of the Soviet nuclear explosions recorded at station BRVK. The symbol sizes are proportional to the sizes of the observed BRVK P wave travel time residuals for these explosions, computed with respect to the predictions of the IASPEI91 (top) and DSS 3-D (bottom) velocity models.

circles), indicating that these observed arrivals are early with respect to IASPEI91, as might be expected for this stable platform region. These residuals are as large as -4 to -8 seconds in the 14- to 18-degree distance range and average to about -3.6 seconds over the entire sample distance range extending from 3 to 19 degrees. The lower panel of Figure 3 shows the corresponding map display of the BRVK residuals computed with respect to the travel times predicted by our preliminary DSS 3-D velocity model. It can be seen that these residuals are generally quite small and fairly randomly distributed spatially. The only notable exception to this general conclusion is the cluster of fairly large negative residuals (< -3 seconds) located almost due north of the station at an average epicentral distance of about 8 degrees. Given the systematic nature of this only remaining significant anomaly, it seems likely that it will eventually be accounted for through the tomographic revision of the velocity model and/or the inclusion of supplemental empirical corrections.

A second validation example is presented in Figure 4 for the far-eastern station TIK. In this case, the ground truth data consist of P wave first arrival times observed from 18 Soviet PNE tests and a sample of Novaya Zemlya underground nuclear tests, and it can be seen that the azimuthal coverage is not as complete as for BRVK. However, once again it can be seen that the residuals computed with respect to the 1-D IASPEI91 model (top) are consistently negative and quite large (i.e. average bias of about -4 seconds), while those computed with respect to the 3-D DSS model (bottom) are significantly smaller and fairly randomly distributed spatially. Similar encouraging results have now been documented for the other Russian stations identified in Figure 2 (Murphy et al, 2001), indicating that our initial DSS 3-D velocity model is generally consistent on average with the ground truth data analyzed to date, and that it represents a significant improvement over the default IASPEI91 model in this region.

It now remains to demonstrate the applicability of this new 3-D velocity model to the determination of improved seismic locations. As an initial step in this process, we have conducted regional location analyses of 14 Soviet PNE events whose map locations are displayed in Figure 5. Each of these explosions was recorded by four or more of the stations identified on this figure. In each case, two different seismic

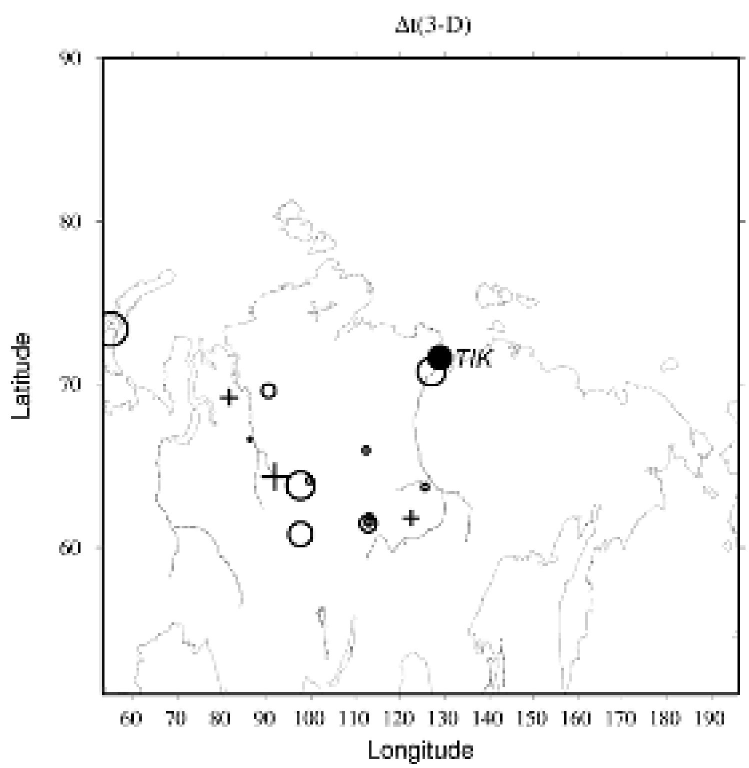


Figure 4. Map locations of the Soviet nuclear explosions recorded at station TIK. The symbol sizes are proportional to the sizes of the observed BRVK P wave travel time residuals for these explosions, computed with respect to the predictions of the IASPEI91 (top) and DSS 3-D (bottom) velocity models.

locations were computed; one using the standard IASPEI91 model and one using travel-time corrections estimated from the DSS 3-D velocity model. That is, predicted corrections to the observed travel times at the stations of Figure 5 were determined with respect to IASPEI91 by ray tracing through the DSS 3-D velocity model, and the explosions were relocated with and without corrections using the same hypocenter inversion code (i.e. LOCSAT). The results of this analysis indicated that the average mislocation for these 14 ground truth events was reduced from 20.4 km to 11.7 km as a result of applying these preliminary station corrections. Since these are predominantly GT1 events, this reduction in average mislocation is highly significant and, therefore, we conclude that the DSS 3-D velocity model does lead to significantly improved seismic locations for this preliminary sample of ground truth events. Similar encouraging relocation results have been documented using our WINPAK3D velocity model of the India/Pakistan region (Johnson and Vincent, 2001), which has led us to conclude that we have formulated a reasonable first order 3-D velocity model for the region which is suitable for refinement via tomographic inversion of suitable independent data sets.

We are currently revising this initial velocity model by applying tomographic inversion techniques to arrival time data observed from well-located explosions and earthquakes. To obtain an initial model for eastern Asia, we have re-parameterized and integrated various global and regional earth models into a universal model. Our parameterization of the universal model is given in terms of a velocity vs. depth profile at each point on a geographic grid. The geographic grid has uniform latitude spacing and, in each of several bands of latitude, uniform longitude spacing. The longitude spacing increases in bands at higher latitude. At each geographic grid-point, the velocity profile is given as velocity/depth pairs at nodes ranging from sea level to a depth of 760 km. Discontinuities in velocity are allowed at the ocean bottom, Moho and the major mantle discontinuities.

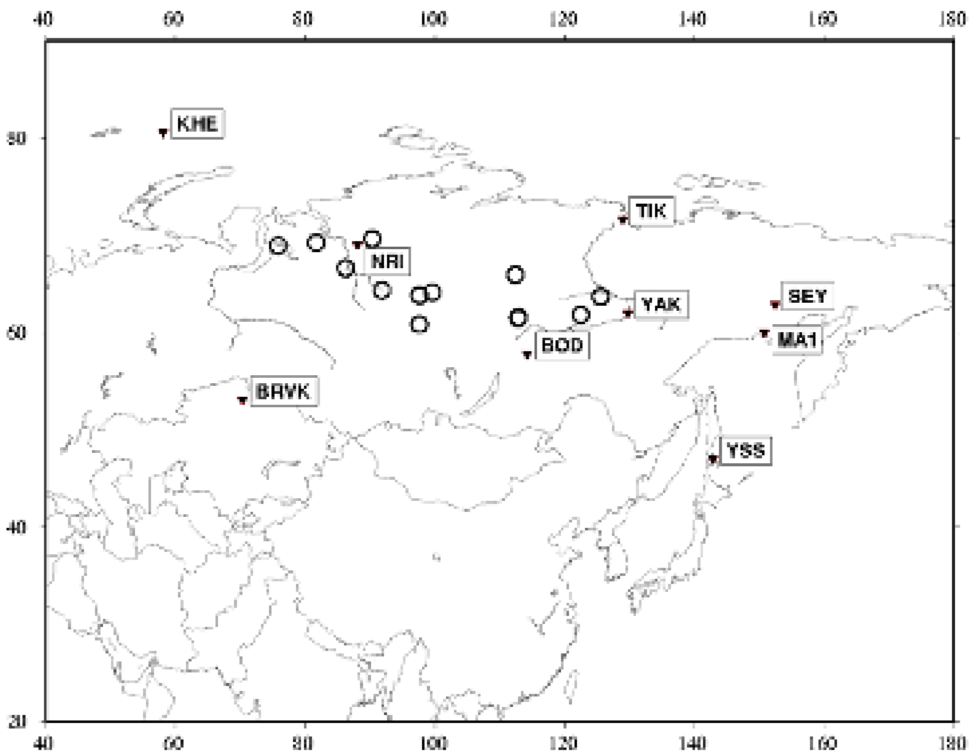
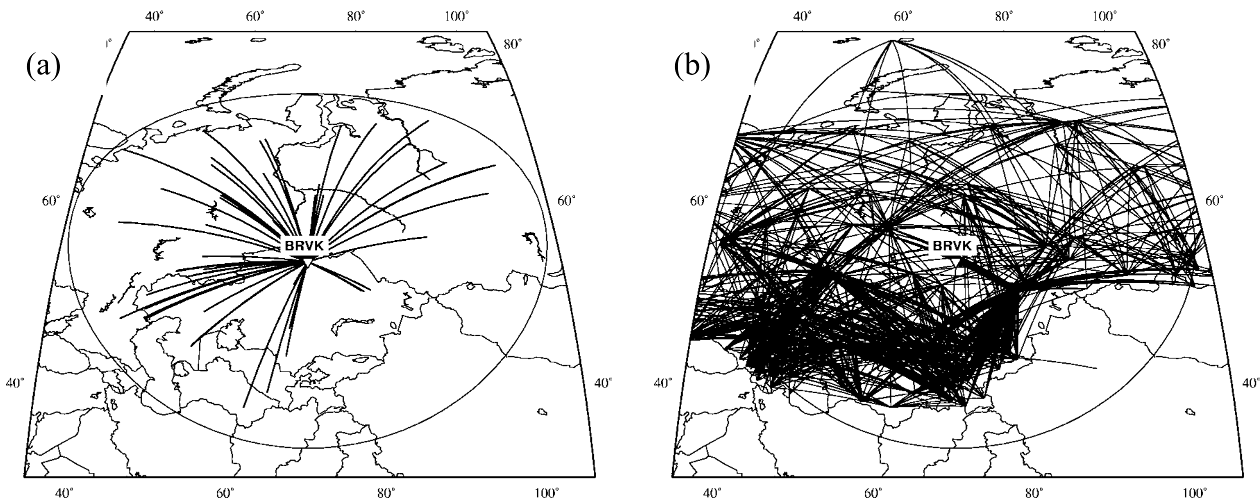


Figure 5. Map locations of 14 selected PNE events (circles), each of which was recorded by 4 or more of the indicated stations (triangles).

Our initial velocity model will be updated to fit regional arrival times observed at IMS and other stations from well-located events. Such events include explosions with known locations, earthquakes located with local networks, or large earthquakes whose locations are well constrained by regional and teleseismic data. To accomplish this, we are developing an inversion algorithm that performs joint velocity tomography and

multiple-event location. The algorithm will relocate the earthquakes in conjunction with revising the parameters of our universal velocity model. Initially, the model update will be restricted to the Pn velocity over a limited geographic region, i.e., the region near Borovoye. The preliminary travel-time data set that have been collected for this region is summarized in Figure 6.



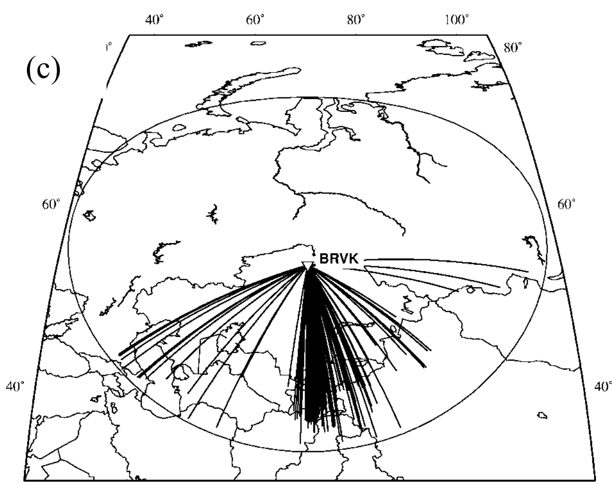


Figure 6. Maps showing great circle paths associated with the P wave first arrival time data that have been assembled for the tomographic analysis of the DSS 3-D velocity model located within 20° of station BRVK. These consist of: (a) Soviet PNE events observed at BRVK, (b) Soviet PNE events observed at stations of the Soviet permanent seismic network in this region and (c) selected well-located Soviet bulletin earthquakes observed at BRVK.

Our inversion approach is formulated as follows. The unknowns are a vector **m** containing the velocity model parameters that are to be estimated (e.g. Pn velocity at each point of the latitude-longitude grid), and the hypocenters and origin times of several events: $(\mathbf{x}_j, t_j), j = 1,\ldots,M$. The data are arrival times, d_{ij} , from each event to a subset of stations indexed as $i = 1,\ldots,N$. The data and unknowns are related by

$$d_{ij} = t_j + T_i\left(\mathbf{x}_j;\mathbf{m}\right) + e_{ij}$$

where e_{ij} is the error in d_{ij} and T_i is a function that computes travel time to station i from an event hypocenter $\mathbf{x}_j$. This function depends on the model parameter vector **m**. Our joint inversion criterion is to minimize an objective function of the form

$$\Psi\left(\mathbf{m}, \mathbf{x}_1, t_1, \ldots, \mathbf{x}_M, t_M\right) = \sum_{ij} \left| d_{ij} - t_j + T_i\left(\mathbf{x}_j;\mathbf{m}\right)\right|^2 / \sigma_{ij}^2 + \tau\left|\mathbf{Lm}\right|^2$$

with respect to all the unknowns. Here, Σ_{ij} is the standard deviation of e_{ij}. The second term of $\mathbf{\Psi}$ imposes a smoothness constraint on the velocity model, with **L** being a regularization operator and τ a regularization parameter. The operator **L** is chosen as a differencing operator with the effect that spatial derivatives of the model velocity are minimized. The parameter τ determines the degree of model smoothness.

Our algorithm performs the minimization of **Ψ** using a combination of conjugate gradients and grid-search techniques. The conjugate gradients method is used to find **m** iteratively, one projection in model space per iteration step. At each conjugate gradients step, grid search is used to minimize **Ψ** with respect to the event origin parameters with **m** fixed, thus updating the $\mathbf{x}_j$ and t_j. The grid search for a given event is performed within a specified epicentral radius and depth range from its initial location, allowing us to handle events of varying ground-truth levels (e.g., GT0, GT5, GT15). Our grid search algorithm is described by Rodi and Toks, 2000.

The forward model for this inverse problem is embodied in the travel time functions T_i. For fixed **x**, we evaluate $T_i(\mathbf{x};\mathbf{m})$ by interpolating a travel-time table stored on a 3-D hypocenter grid. The grid is created by applying the Podvin-Lecomte (P-L) finite-difference travel-time algorithm to the earth model defined by **m**, using the location of the *i*th station as the "source" in the calculation. We have developed the necessary algorithms for mapping our universal velocity model to a Cartesian block model needed by the P-L algorithm, and for mapping the 3-D Cartesian travel-time grids to geographic grids. Additionally, the P-L algorithm has been extended to compute the sensitivities of travel times to block velocities, as needed by the conjugate gradients method. The sensitivities are mapped from Cartesian blocks to the universal model parameterization. We note that our joint inversion algorithm is fully nonlinear with respect to both the velocity model and event locations since travel-time modeling and event relocation are performed for each update of **m**. However, this comes at a high computational price and we are also allowing for multiple steps of the conjugate gradients iteration before the P-L modeling is repeated.

Work is also progressing on the definition of more refined starting velocity models for other areas of the Group 1 region. Thus, Chinese earthquake bulletin data are being inverted to define variations of crust and upper mantle structure throughout that country, and currently available published research is being surveyed for other areas of interest. For example, published data on the Korean peninsula are being reviewed and integrated to formulate a velocity model for use in the calibration of IMS station KSRS. Such studies include the waveform analysis of teleseismic pPM and pP phases for an event offshore of North Korea that has provided estimates of Moho depths for five areas in the border regions between northern Korea and northeastern China (Shin and Baag, 2000). These estimates varied from 25 to 35 km, in good agreement with the crustal thickness of 29-36 km over North Korea inferred by Pak et al (1987) using regional gravity and seismic sounding data. Reported velocity profiles for the Korean peninsula vary, with anywhere from 1 to 8 crustal layers, and include an unusual low-velocity crustal layer which has been inferred to lie beneath the Yangsan Fault region in eastern South Korea (Kim, 1999). It is anticipated that the initial regional velocity models determined on the basis of such published data will subsequently be tested using available ground truth data and refined using the joint tomographic inversion and hypocenter relocation techniques which were described above.

CONCLUSIONS AND RECOMMENDATIONS

During the past year we have continued with our comprehensive program to calibrate the 30 Group 1 IMS stations of eastern Asia in an attempt to improve seismic location capability in that area. A preliminary composite 3-D velocity model for the entire region has been formulated and an efficient finite difference ray tracing code for computing travel times through such models has been implemented and tested. Evaluation of the DSS velocity model for the FSU has continued, and ground truth Soviet PNE data recorded at or near the Group 1 IMS stations BRVK, NRI, TIK, YAK, PDY and AAK have been carefully analyzed and used to produce travel-time residual maps with respect to both the default IASPEI91 travel-time table and the travel times predicted by ray tracing through our preliminary 3-D velocity model. It has been demonstrated that the travel-time residuals with respect to our 3-D model are significantly smaller than those computed with respect to the corresponding IASPEI91 model, with most stations showing an average bias near zero for the former model. An initial event location test conducted using data recorded at these "IMS stations" from 14 Soviet PNE tests has been conducted and used to demonstrate that the new 3-D velocity model provides significantly more accurate seismic locations for these ground truth explosions than does the default IASPEI91 model. Similarly encouraging results have been obtained from seismic location analyses of the data recorded from a ground truth earthquake located near the IMS station PRPK in Pakistan, in that the seismic locations determined using our WINPAK3D velocity model with various subsets of the observed data have been shown to be significantly

more accurate than the corresponding locations obtained using the IASPEI91 model. Current effort on the project centers on the development of more detailed velocity models for the remaining Group 1 IMS station areas and on the refinement of the preliminary 3-D velocity models through tomographic inversion analyses. A sophisticated tomographic inversion algorithm has now been implemented which will be applied to a variety of explosion and earthquake travel-time data collected for events in the Group 1 IMS station region. In this approach, a joint inversion will be performed to simultaneously determine earthquake locations, revised velocity model parameters and empirical corrections in a statistically consistent fashion, which takes full account of all available data, as well as the uncertainties in these data. The resulting refined 3-D velocity models and associated empirical corrections will then be used to update the SSSC estimates for the Group 1 IMS stations.

REFERENCES

Johnson, M and C. Vincent (2001), "Development of a 3-D Velocity Model of the India-Pakistan Region for Improved Seismic Event Location," submitted to *Bull. Seism. Soc. Am*., February.

Kim, W. (1999), P-wave velocity structure of upper crust in the vicinity of the Yangsan Fault region," *Geosciences Journal*, **1**, 17-22.

Murphy, J., W. Rodi, M. Johnson, I. Kitov, D. Sultanov, B. Barker, C. Vincent, V. Ovtchinnikov and Y. Shchukin (2001), "Seismic Calibration of Group 1 IMS Stations in Eastern Asia for Improved IDC Event Location," SAIC-01/1021.

Pak, C. S., I.T. O and P. S. Kim (1987), "A study for determination of the crustal thickness of Korea," *Geology and Geography Chosen* (Korea), **6**, 3-7.

Podvin, P. and I. Lecomte (1991), "Finite Difference Computation of Traveltimes in Very Contrasted Velocity Models: A Massively Parallel Approach and Its Associated Tools," *Geophys. J. Int.* **105**, 271-284.

W. Rodi and M.N. Toksöz (2000). Grid-search techniques for seismic event location, *Proceedings*, 22nd Annual DoD/DOE Seismic Research Symposium, New Orleans.

Shin, J. S. and C. E. Baag (2000), "Moho depths in the border region between northern Korea and northeastern China from waveform analysis of teleseismic pMP and pP phases," *Geosciences Journal*, **4**, 313-320.